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Significant progress was made in a number of apsects of nonlinear and stochastic systems. An important problem in the adaptive control of a finite state Markov chain was solved, and significant progress was made along more general directions. A controlled switching diffusion model was developed to study the hierarchical control of flexible manufacturing systems and significant results were obtained. In the area of deterministic nonlinear systems the work continued on nonlinear observers and linearizable dynamics. Finally, some important problems in the area of discrete event systems were solved.

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"ADAPTIVE CONTROL OF NONLINEAR AND STOCHASTIC SYSTEMS"

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Significant progress was made in a number of aspects of nonlinear and stochastic systems. An important problem in the adaptive control of a finite state Markov chain was solved, and significant progress was made along more general directions. A controlled switching diffusion model was developed to study the hierarchical control of flexible manufacturing systems and significant results were obtained. In the area of deterministic nonlinear systems we continued our work on nonlinear observers and linearizable dynamics. Finally, some important problems in the area of discrete event systems were solved.

1. SUMMARY OF RESEARCH PROGRESS AND RESULTS

During the year supported by this grant, we have made significant progress both in areas we proposed to investigate and in related areas. Ir this section, we summarize the progress in those areas that have resulted in publications.

1.1. Stochastic Control.

1.1.1. Stochastic Control of Markov Processes.

We have continued our research program in a major new area involving adaptive estimation and control problems for stochastic systems involving either incomplete (or noisy) observations of the state or nonlinear dynamics. The first class of problems we have been studying involves finite state Markov chains with incomplete state observations and unknown parameters; in particular, we have studied certain classes of quality control, replacement, and repair problems.

We have first considered a quality control problem in which a system, such as a manufacturing unit or computer communications network, can be in either of two states: good or bad. Control actions available to the inspector/decision-maker are:

(a) produce without inspection,
(b) produce and inspect; or
(c) repair.

Under actions (a) and (b) the system is subject to Markovian deterioration, while a repair puts the unit in the good state by the next decision time. Informative data might become available while producing without inspection, and inspection is not always perfect. Hence the problem is modeled as a partially observed Markov decision process (POMDP). Furthermore, we assume that deterioration of the system depends on an unknown parameter, namely the probability of the state going from the good to the bad state in one time epoch when no repair is done. For the case of known parameters, we have shown in our past research that there is an optimal policy for the infinite horizon average cost criterion that is of the control limit (bang-bang) type. The adaptive stochastic control problem is, however, *much* more difficult than the adaptive estimation problem, because the presence of feedback causes the system transitions to depend on the parameter estimates and introduces discontinuities.

In [3] and [7], we have analyzed algorithms for this quality control problem in

which the parameter estimates are updated only after the system is repaired; such algorithms are analogous to those in which estimates in queueing systems are updated only after each busy cycle. Since the system is returned to the "good" state after repair, one obtains a perfect observation of the state at that time, and our algorithm uses the observation at the next time to estimate the parameter. Hence, we develop parameter estimation techniques based on the information available after actions that reset the state to a known value. At these times, the augmented state process "regenerates," its future evolution becoming independent of the past. Using the ODE method, we show that two algorithms, one based on maximum likelihood and another based on prediction error, converge almost surely to the true parameter value. In addition, we modify the method of Shwartz and Makowski to prove optimality of the resulting certainty equivalent adaptive policy, assuming only the existence of *some* sequence of parameter estimates converging almost surely to the true parameter value. Again, the discontinuities and partial observations in this problem preclude the direct use of previously existing methods, but we have been able to generalize the method to problems such as this. Also, we have avoided the very strong standard assumption that the parameter estimates converge almost surely to the true parameter value under *any* stationary policy.

A project in surveying the literature on the ergodic control problem for discrete-time control Markov processes was completed. This was a major effort which puts together a comprehensive account of the considerable research on this problem over the past three decades. Our exposition ranges from finite to Borel state and action spaces and includes a variety of methodologies to find and characterize optimal policies. We have included a brief historical perspective of the research efforts in this area and have compiled a substantial bibliography. In the process we have identified several important questions which are still left open to investigation.

1.1.2. Stochastic Control Switching Diffusions.

In [4] and [10] we study a controlled switching diffusion process that arises in numerous applications of systems with multiple modes or failure modes, including the hierarchical control of flexible manufacturing systems. A flexible manufacturing system (FMS) consists of a set of workstations capable of performing a number of different operations and interconnected by a transportation mechanism. An FMS produces a family of parts related by similar operational requirements or by belong-

ing to the same final assembly. The rapidly growing range of applicability of FMS includes metal cutting, assembly of printed circuit boards, integrated circuit fabrication, automobile assembly lines, etc. The high capital cost of an FMS demands very efficient management of production and maintenance (repair/replacement) scheduling so that uncertain events such as random demand fluctuations, machine failures, inventory spoilages, sales returns, etc. can be taken care of. The large size of the system and its associated complexities make it imperative to divide the control or management into a hierarchy consisting of a number of levels. Thus, the overall complex problem is reduced to a number of manageable subproblems at each level, and these levels are linked by means of a hierarchical integrative system. It is of paramount importance to develop and study an appropriate mathematical model which will facilitate to find on line implementable optimal feedback policies.

We view an FMS as a system consisting of a number of workstations, with each workstation having a set of identical machines. A collection of a number of types of different parts is produced. The model we are using involves a hybrid process in continuous time whose state is given by a pair $\big(X(t), S(t)\big)$. Here, $X(t)$ denotes the downstream buffer stock of parts, which may have a negative value to indicate a backlogged demand. The continuous component $X(t)$ is governed by a controlled diffusion process with a drift vector which depends on the discrete component $S(t)$. Thus, $X(t)$ switches from one diffusion path to another as the discrete component $S(t)$ jumps form one state to another. On the other hand, the discrete component $S(t)$, denoting the number of operational machines, is influenced by the inventory size and production scheduling, and can also be controlled by various decisions such as produce, repair, replace, etc. Hence, $S(t)$ evolves as a "controlled Markov chain" with a transition matrix depending on the continuous component.

This FMS model motivates the study of a stochastic optimization problem in a more abstract setting which is manifested in numerous other situations. For example, it is encountered in a hybrid model proposed for the study of dynamic phenomena in large scale interconnected power networks, in macroeconomic problems and in dynamic renewal problems in general. Our treatment of the optimization problem is based on a convex analytic approach which is interesting in its own right and would be more flexible and powerful for certain other purposes, e.g. pathwise average cost problem or problem with several constraints where the analytic approach

does not seem to be amenable.

1.2. Nonlinear Systems.

Most of the research activity on adaptive control of nonlinear systems is still focused on the full-state feedback case, although output-feedback results are beginning to appear. Adaptive output-feedback designs follow either a direct model-reference path or an indirect path via adaptive observers. Current research on adaptive observers for nonlinear systems, indicates that the indirect path may become promising for adaptive control. Continuing our work in this direction we studied in [9] the problem of construction of observers for nonlinear affine systems with linearizable error dynamics. Our aim was to obtain a design for which the diffeomorphism transforming the nonlinear system into a nonlinear observer form is independent of the choice of the control input. Working with one-forms we have also dealt with the problem of constructing approximate observers up to a certain desired order. This is very important for systems where the rather stringent conditions necessary for the exact observer design are not met. We have extended these results to the multiple-input, multiple-output case.

Approximate linearization of nonlinear systems becomes important for systems where the nonlinearities are severe enough that exact linearization fails. An approximate method that linearizes the system up to a certain order has originally been proposed by Krener. Since less restrictive conditions are required for approximate linearization, this technique offers the means of enlarging the class of nonlinear systems to which linearizing techniques are applicable. In [2] we study the problem via differential forms. Despite the fact that this is only the dual to the approach that Krener followed, we show that it results in substantial computational savings. Our method is constructive and offers a simple solution to the problem.

In [1] we studied the controllability problem of nonlinear systems along closed orbits. The results extend previous work in the field on local controllability along a reference trajectory.

1.3. Other Related Research.

We have also made progress in a number of other related areas of research. We have started working on a particular state estimation problem involving interconnected power systems. The objective here is to develop a methodology for the optimal placement of instrumentation to detect the location and type of harmonic

sources in a power network. Harmonic distortion in distribution power systems is reaching detrimental levels and causes problems such as overheating and failure of equipment, malfunction of protective equipment, nuisance tripping of sensitive loads, and interference with communication networks. Most of the harmonics simulation work performed thus far has addressed harmonic injection and propagation in power systems, or, in other words, the problem of harmonic power flow analysis, which amounts to modeling the injection currents at harmonic frequencies and then calculating bus voltages, line flows, and distortion. The converse of this problem, is to identify the injection currents at harmonic frequencies based on measurements of selected bus voltages and line flows. The number of instruments that can be installed in a network to furnish on-line measurements is limited, mainly due to their high cost. The placement of these devices becomes, therefore, very critical and constitutes a problem that has recently attracted much attention in the scientific community. The problem described is not confined to power systems—more generally, the question addressed here is the optimal location of sensors for state estimation. Our work so far in this problem is summarized in [6]. We formulate the problem in a rigorous mathematical fashion and identify some important inherent pathologies. Further research in this topic is under way.

In the area of discrete event dynamical systems (DEDS), we studied the supervisor synthesis problem through the use of synchronous composition of the plant and supervisor, thus simplifying the DEDS control methodology. In addition, we derived optimal algorithms for the computation of supremal controllable sublanguages. Corresponding infinite horizon supervisory control problems were considered in [11]. Stability and stabilization of DEDS's are studied in [12]; these notions are presented in a more general setting than in previous work. Efficient tests for stability and stabilizability are derived.

2. PUBLICATIONS

Journal Publications

[1] K. Nam and A. Arapostathis, *A Sufficient Condition for Local Controllability of Nonlinear Systems Along Closed Orbits*, IEEE Transactions on Automatic Control (to appear).

[2] K. Nam, A. Arapostathis and K. K. Lee, *Some Numerical Aspects of Approximate Linearization of Single Input Nonlinear Systems*, submitted to International Journal of Control.

[3] E. Fernández-Gaucherand, A. Arapostathis and S. I. Marcus, *Analysis of an Adaptive Control Scheme for a Partially Observed Markov Decision Process*, submitted to IEEE Transactions on Automatic Control.

[4] M. K. Ghosh, A. Arapostathis and S. I. Marcus, *Optimal control of switching diffusions with application to flexible manufacturing systems*, submitted to SIAM J. Control and Optimization.

[5] A. Arapostathis, V. S. Borkar, E. Fernández-Gaucherand, M. K. Ghosh and S. I. Marcus, *Discrete-Time Controlled Markov Processes with Average Cost Criterion: A Survey*, submitted to SIAM J. Control and Optimization.

[6] J. E. Farach, W. M. Grady and A. Arapostathis, *Optimal Sensor Placement for Estimating the Location of Harmonic Sources in a Power System*, submitted to IEEE Transactions on Power Apparatus and Systems.

[7] R. Kumar, V. Garg and S. I. Marcus, *On Controllability and Normality of Discrete Event Dynamical Systems*, Systems & Control Letters **17** (1991), 157–168.

Other Publications

[8] S. I. Marcus, E. Fernández-Gaucherand and A. Arapostathis, *Adaptive Control and Cost Sensitivity of Stochastic Systems with Continuous State and Parameters, and Logical Controls*, Proc. 1991 American Control Conference Boston, MA, June 26–28, 1991.

[9] K. Nam and A. Arapostathis, *Observers for Nonlinear Affine Systems with Linearizable Error Dynamics*, Proc. 1991 International Symposium on the Mathematical Theory of Networks and Systems, Kobe, Japan, June 17–21, 1991 (to appear).

[10] M. K. Ghosh, A. Arapostathis and S. I. Marcus, *An optimal control problem arising in flexible manufacturing systems*, Proc. 30th IEEE Conference or. Decision and Control Brighton, England, December 11–13, 1991.

[11] R. Kumar, V. Garg and S. I. Marcus, *On ω-Controllability and ω-Normality of DEDS*, Proc. 1991 American Control Conference, Boston, MA, June 26-28, 1991, 2905–2910.

[12] R. Kumar, V. Garg and S. I. Marcus, *Stability of Discrete Event System Behavior*, Proc. IFAC International Symposium on Distributed Intelligence Systems, Arlington, VA, August 13-15, 1991, 13–18.

3. RESEARCH PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

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4. PAPERS PRESENTED

[i] K. Nam and A. Arapostathis, *Observers for Nonlinear Affine Systems with Linearizable Error Dynamics*, 1991 International Symposium on the Mathematical Theory of Networks and Systems Kobe, Japan, June 17–21, 1991.

[ii] S. I. Marcus, E. Fernández-Gaucherand and A. Arapostathis, *Adaptive Control and Cost Sensitivity of Stochastic Systems with Continuous State and Parameters, and Logical Controls*, 1991 American Control Conference Boston, MA, June 26–28, 1991.

[iii] M. K. Ghosh, A. Arapostathis and S. I. Marcus, *Optimal control of switching diffusions modelling a flexible manufacturing system*, Stochastic Theory and Adaptive Control Workshop Lawrence, KS, September 26–28, 1991.

[iv] S. I. Marcus, A. Arapostathis and E. Fernández-Gaucherand, *Adaptive control of stochastic systems with continuous state and parameters, and logical controls*, Stochastic Theory and Adaptive Control Workshop Lawrence, KS, September 26–28, 1991.

[v] M. K. Ghosh, A. Arapostathis and S. I. Marcus, *An optimal control problem arising in flexible manufacturing systems*, 30th IEEE Conference on Decision and Control Brighton, England, December 11–13, 1991.

[vi] R. Kumar, V. Garg and S. I. Marcus, *On ω-Controllability and ω-Normality of DEDS*, 1991 American Control Conference, Boston, MA, June 26-28, 1991.

[vii] R. Kumar, V. Garg and S. I. Marcus, *Stability of Discrete Event System Behavior*, IFAC International Symposium on Distributed Intelligence Systems, Arlington, VA, August 13-15, 1991.